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A METHOD OF CREATING AND ANALYZING ACTIVE FINITE ELEMENTS

Background of the Invention

5   The present invention pertains to a method of creating
active finite elements for studying mechanical properties
of active structures. One of the applications is to
study the mechanical properties of skeletal muscles,
which is important to industrial design of sport,
10   automotive, medical and health equipment for exercise,
rehabilitation and treatments, for example.

The basic ideas of the finite element method are
presented in a paper "Stiffness and Deflection Analysis
15   of Complex Structures" in 1956. In 1960, the name "finite
element" was coined by R.W. Clough in a paper "The Finite
Element Method in Plane Stress Analysis" on plane
elasticity problems. The finite element method uses
numerical analysis to obtain approximate solutions for
20   solving various engineering problems. A structure or
region to be analized is broken down into many small and
interconnected subregions. These subregions are called
finite elements.

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Traditionally, the finite element method has been

frequently used in design processes in civil, mechanical

and aeronautical engineering. Recently, the finite

element method has been successfully extended to solve

5   other types of engineering problem, like geomechanics,

acoustics, electro-magnetic fields, field dynamics and

heat transfer. Some attention has also been given to the

micro- and macro-analyses of advanced composite

materials.

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In stress/displacement finite element analyses, external

conditions such as boundary conditions and loads can be

prescribed on nodes, element faces and element bodies.

Boundary conditions generally include prescribed

15   displacement, prescribed velocity and prescribed

acceleration. Loads can include concentrated forces,

surface tractions, moments, and body forces due to

centrifugal acceleration, rotary acceleration, and

gravity. When all nodes in a node set are prescribed a

20   displacement in certain degrees of freedom, these nodes

will displace from their original positions in the

prescribed direction after a specified time period. When

a surface traction such as pressure force is applied onto

the surface of an element set, these elements may deform,

25   displace or rotate. Thus, if no appropriate external

conditions are prescribed on them, any nodes or elements

are passive and do not have any motion.

However, some structures like skeletal muscle are active

5   in nature. Whenever there is an electrical stimulation

applied to skeletal muscle, the muscle can contract under

no prescribed externally applied displacement and load.

As material properties of current finite elements are

limited to be passive, simulation of active structures

10   and the interactions with passive ones are almost

impossible to perform. Thus, the foregoing calls for a

novel method to model the mechanical properties of active

structures like human beings, animals, and smart

structures.

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Object of the Invention

It is an object of the present invention to devise a

method of creating active finite elements for studying

20   mechanical properties of active structures.

Disclosure of the Invention

There are disclosed herein a method for creating and

25   analyzing active finite elements comprising the steps of:

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a)   constructing the active finite elements with a

combinations of motor elements, dashpot elements and

spring elements,

b)   defining the motor element using a time series

5   function, and

c)   constructing a model with the active finite

elements, and

d)   analyzing the model using a finite element code.

10   Preferably, the finite element code is a conventional

code.

Preferably, said finite elements are one-dimensional or

two- dimensional or three-dimensional.

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Under no applied external conditions like prescribed

boundary conditions and loads, active finite elements can

be activated to displace, rotate or deform by the

prescribed time series function.

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Each active finite element must consist of at least one

motor element. The composition of an active finite

element can be any combinations of motor element(s),

dashpot element(s) and/or spring element(s).

The time series function pre-describes the strain and/or

its rates of the material of the motor element. By

incorporating this function into the stress-strain

relation, the motor element can be created to construct

5   the active finite element.

Active structures include but are not limited to human

beings, animals and smart structures.

10   Brief Description of the Drawings

A preferred form of the invention will now be described

by way of example with reference to the accompanying

drawings, wherein:-

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Fig.1 is a one-dimensional representation of muscle-

tendon complex,

Fig.2 illustrates the stress distribution in the muscle-

20   tendon complex induced by the extension of the motor

element at a positive strain rate, $c = 0.25s^{-1}$ in two

seconds.

Fig.3 illustrates the stress distribution in the muscle-

25   tendon complex induced by the contraction of the motor

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element at a negative strain rate, $c = -0.25s^{-1}$ in two

seconds, and

Fig.4 shows normalized force at the fixed end of the

5   spring element versus strain rate

Table 1 shows the material parameters for the muscle-

tendon complex.

10   Detailed Description of the Preferred Embodiment

An active finite element such as a muscle tissue 2

contains at least one motor element 10. Dashpot

element(s) 11 and/or spring element(s) 12 with a suitable

15   arrangement can be connected to the motor element to

construct the active element. Each of these basic

elements has their own properties. Even under no applied

external conditions like prescribed boundary conditions

and loads, motor elements can be activated to contract or

20   expand by a time series function.

The time function governs the strain and its rates of the

material of the motor element. The dashpot elements have

viscous properties while spring elements are elastic or

25   hyperelastic or hypoelastic. By suitable combinations of

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the motor elements, dashpots and springs, an active

finite element can be designed to have different

constitutive material properties for studying mechanical

properties of various different types of active

5   structure. Incorporating a user-defined sub-programme

into a conventional finite element code creates the

active finite element with desired material properties.

One-dimensional, two-dimensional or three-dimensional

finite element models are then built for active

10   structures by using the created active finite elements.

In addition, suitable finite element meshing, prescribed

boundary conditions, load conditions and analysis steps

should be defined for predicting the motion and stress-

strain distribution of active structures.

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Example : Active finite elements for biomechanical

studies

This example describes how a three-dimensional active

20   finite element is created for biomechanical studies. The

active finite element is then applied to model the motion

of skeletal muscle tissue. The active finite element is

created by incorporating a user-defined sub-programme

into the finite element code ABAQUS version 5.8. The

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active finite element is controlled by a time function

that may describe the neuromuscular characteristics.

One dimensional representation of a simple muscle-tendon

5   complex is shown in Fig.1. In this example, the active

finite element 2 is constructed by one motor element 10,

a combined viscoelastic element 3 including one dashpot

element 11 and two spring elements 12(k_1 & k_2). The tendon

4 is represented by a spring element 12 (k_3).

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Suppose the strain, $\varepsilon(t)$ of the motor element is

represented by a linear time function:

$$\varepsilon(t) = ct + c_0$$

(1)

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where c, c_0, t are the strain rate coefficient, the

initial strain and the time variable respectively. For

instance, c_0 is set to zero.

20   At a time, t, the rate of extension or contraction of the

motor element can be controlled by the value of c. When c

is positive, the motor element will elongate actively. On

the other hand, the value of c is set to be negative, the

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motor element will shorten actively to produce

contractile force.

For a three-dimensional motor element, the incremental

5   stress-strain relationships in this example, are

expressed as:

$$\Delta\sigma_{xx}(t) = \Delta\varepsilon_{xx}(t) - c\Delta t$$

(2)

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$$\Delta\sigma_{yy}(t) = \Delta\varepsilon_{yy}(t) - c\Delta t + a$$

(3)

$$\Delta\sigma_{zz}(t) = \Delta\varepsilon_{zz}(t) - c\Delta t + b$$

15   (4)

where σ_{xx}, σ_{yy} and σ_{zz} are the induced stress components

along three principal axes of the motor element. The

constants a and b are used to control the lateral

20 contraction and expansion of the element for volume

conservation. For simplicity, shearing is ignored in the

motor element in this example.

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The Jacobian matrix has the following terms:

$$\frac{\partial \Delta \sigma_{xx}}{\partial \Delta \varepsilon_{xx}} = \frac{\partial \Delta \sigma_{yy}}{\partial \Delta \varepsilon_{yy}} = \frac{\partial \Delta \sigma_{zz}}{\partial \Delta \varepsilon_{zz}} = 1$$

(5)

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$$\frac{\partial \Delta \sigma_{xx}}{\partial \Delta \varepsilon_{yy}} = \frac{\partial \Delta \sigma_{xx}}{\partial \Delta \varepsilon_{zz}} = \frac{\partial \Delta \sigma_{yy}}{\partial \Delta \varepsilon_{zz}} = 0$$

(6)

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$$\frac{\partial \Delta \sigma_{xy}}{\partial \Delta \varepsilon_{xy}} = \frac{\partial \Delta \sigma_{xz}}{\partial \Delta \varepsilon_{xz}} = \frac{\partial \Delta \sigma_{yz}}{\partial \Delta \varepsilon_{yz}} = 0$$

(7)

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Suppose the muscle-tendon complex has material properties listed in Table 1.

MOTOR ELEMENT		
1	Strain rate, c	-0.5 to +0.5s^{-1}
2	Time period, t	2 seconds
3	Material constants, a or b	0.4c
COMBINED VISCOELASTIC ELEMENT		
1	Young's modulus, E	5 MPa
2	Poisson's ratio, v	0.48
3	Maximum number of terms in the Prony series, n	1
2	The modulus ratio in the first term in the Prony series expansion of the shear relaxation modulus, $\bar{g}_1'$	0.5
3	The modulus ratio in the first term in the Prony series expansion of the bulk relaxation modulus, $\bar{k}_1'$	0.5
4	The relaxation time for the first term in the Prony series expansion, t_i^G or t_i^K	0.8 seconds
TENDON		
1	Young's modulus, E	1 MPa
2	Poisson's ratio, v	0.3

Table 1

As both ends of the muscle-tendon complex have been

constrained in the y-direction, this means that the

combined viscoleastic element and the tendon have to

retract in response to a strain generated by the

5   extension of the motor element at a positive strain rate

(say $c = -0.25s^{-1}$). As the elastic modulus of the combined

viscoelastic element is set to be greater than that of

the tendon, the former retracts less than the latter as

in Fig.2. With the opposition from these two elements,

10 the extension of the motor element becomes much less than

that can be induced by only one motor element. Therefore,

a highest compressive stress in the y-direction is

induced in the region connected to the combined

viscoelastic element as in Fig.2.

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When the strain rate of the motor element is changed from

a positive to a negative value, the motor element

retracts while the combined viscoelastic element and the

tendon extend as in Fig.3. The deformed motor element is

20 no longer a rectangle but it expands much greater at its

fixed end. It is because the motor element is only fixed

at the y-direction while it can freely move at the x and

y directions. Again, the distance extended by the

combined viscoelastic element is less than that moved by

25 the tendon. As the stiffness of the combined viscoelastic

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element is greater than that of the motor element, the

retracting distance of the motor element shown in Fig.3

becomes much less than that can be induced by only one

motor element. This induces a highest tension force at

5   the fixed end of the motor element in the y-direction as

in Fig.3. The normalized force is measured at the fixed

end of the tendon. Its relation with the strain rate is

plotted in Fig.4.